

Double-parton scattering cross sections in proton-nucleus and nucleus-nucleus collisions at the LHC

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Abstract

Simple generic expressions to compute double-parton scattering (DPS) cross sections in high-energy proton-nucleus and nucleus-nucleus collisions, as a function of the corresponding single-parton cross sections, are presented. Estimates of DPS contributions are studied for two specific processes at LHC energies: (i) same-sign W-boson pair production in p-Pb, and (ii) double- J/ψ production in Pb-Pb, using NLO predictions with nuclear parton densities for the corresponding single-parton cross sections. The expected DPS cross sections and event rates after typical acceptance and efficiency losses are also given for other processes involving J/ψ and W,Z gauge bosons in p-Pb and Pb-Pb collisions at the LHC.

1. Introduction

Hadrons (protons, nuclei) are composite particles with a finite transverse size, whose internal parton density rises rapidly with increasing colliding energies. Such a fact leads naturally to a large number of multiple parton interactions (MPI) occurring in each single proton-proton (p-p), proton-nucleus (p-A), and nucleus-nucleus (A-A) collision at LHC energies [1, 2]. Many basic p-p event properties –such as the distributions of hadron multiplicities in “minimum bias” collisions and the underlying event activity in hard scattering interactions– can only be reproduced by Monte Carlo generators by including MPI at semi-hard scales of order $O(1 - 3 \text{ GeV})$, modeled through an impact-parameter description of the transverse parton profile of the colliding protons. The experimental evidence for the occurrence of double-parton scatterings (DPS) producing in the same collision two independently-identified particles at harder scales, $O(3 - 100 \text{ GeV})$, is however scarcer. The study of DPS processes provides valuable information on the transverse distribution of partons in hadrons [3], on multi-parton correlations in the hadronic wave functions [4], as well as on backgrounds for new physics signals. The importance of DPS in p-A and A-A collisions has been quantitatively highlighted for the first time in Refs. [5, 6]. A summary of those results is presented below together with new estimates of DPS cross sections for various double hard processes in nuclear collisions at the LHC.

In a generic model-independent way, one can write the DPS cross section in p-p collisions as the product of the single-parton scattering (SPS) cross sections, σ^{SPS} –computable perturbatively to a given order in the strong coupling α_s by convoluting the partonic subprocess cross sections with the corresponding parton distribution functions (PDF)– normalized by an effective cross section $\sigma_{\text{eff,pp}}$ characterizing the transverse area of the hard partonic interactions:

$$\sigma_{(pp \rightarrow ab)}^{\text{DPS}} = \left(\frac{m}{2} \right) \frac{\sigma_{(pp \rightarrow a)}^{\text{SPS}} \cdot \sigma_{(pp \rightarrow b)}^{\text{SPS}}}{\sigma_{\text{eff,pp}}}, \quad (1)$$

where the combinatorial factor $m/2$ accounts for indistinguishable ($m = 1$) and distinguishable ($m = 2$) final-states. A numerical value $\sigma_{\text{eff,pp}} \approx 15$ mb has been obtained in p-p at the LHC from empirical fits to W+dijets distributions sensitive to DPS contributions [7, 8]. One can identify $\sigma_{\text{eff,pp}}$ with the inverse of the proton overlap-function squared: $\sigma_{\text{eff,pp}} = \left[\int d^2b \, t^2(\mathbf{b}) \right]^{-1}$ under the two following assumptions: (i) the double-PDF can be decomposed into longitudinal and transverse components, with the latter expressed in terms of the overlap function $t(\mathbf{b}) = \int f(\mathbf{b}_1) f(\mathbf{b}_1 - \mathbf{b}) d^2b_1$ for a given parton transverse thickness function $f(\mathbf{b})$ representing the effective transverse overlap area of partonic interactions that produce the DPS process, and (ii) the longitudinal component reduces to the “diagonal” product of two independent single-PDF. The fact that the measured $\sigma_{\text{eff,pp}}$ is about a factor of two smaller than estimates based on naive geometric descriptions of the proton [9], and ascertaining the evolution of $\sigma_{\text{eff,pp}}$ with collision energy, remain two important open issues in DPS studies.

In p-A collisions, the parton flux is enhanced by the number A of nucleons in the nucleus and the SPS cross section is simply that of proton-nucleon (p-N) collisions (accounting for shadowing effects in the nuclear PDF) scaled by A [10], whereas the DPS cross sections is further enhanced due to interactions where the two partons of the nucleus belong to the same nucleon and to two different nucleons [11]. The corresponding DPS cross section reads [5]:

$$\sigma_{pA \rightarrow ab}^{\text{DPS}} = \left(\frac{m}{2} \right) \frac{\sigma_{pN \rightarrow a}^{\text{SPS}} \cdot \sigma_{pN \rightarrow b}^{\text{SPS}}}{\sigma_{\text{eff,pA}}}, \text{ with } \sigma_{\text{eff,pA}} = \frac{\sigma_{\text{eff,pp}}}{A + \sigma_{\text{eff,pp}} F_{pA}} \approx 22.6 \, \mu\text{b}, \quad (2)$$

where $F_{pA} = \frac{A-1}{A} \int T_{pA}^2(\mathbf{r}) d^2r$ with the standard Glauber nuclear thickness function $T_{pA}(\mathbf{r})$ [10], and the last numerical equality holds for p-Pb using $A = 208$, $\sigma_{\text{eff,pp}} = 15$ mb and $F_{pA} = 30.4 \, \text{mb}^{-1}$. The DPS cross sections in p-Pb are thus enhanced by a factor of $\sigma_{\text{eff,pp}}/\sigma_{\text{eff,pA}} \approx 3A \approx 600$ compared to p-p. Exploiting such a large expected DPS signal allows one to determine the value of $\sigma_{\text{eff,pp}}$ independently of other p-p measurements, given that the parameter F_{pA} depends on the comparatively better known transverse density profile of nuclei.

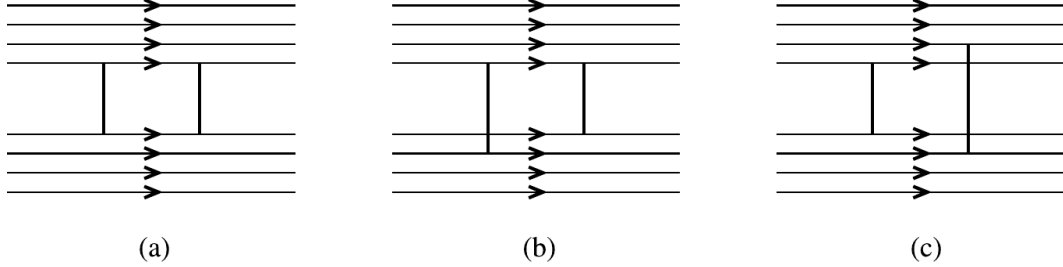


Figure 1. Schematic DPS contributions in A-A collisions: (a) The two colliding partons belong to the same pair of nucleons, (b) partons from one nucleon in one nucleus collide with partons from two different nucleons in the other nucleus, and (c) the two colliding partons belong to two different nucleons from both nuclei.

In the A-A case, the single-parton cross section is that of p-p (again, modulo nuclear PDF shadowing corrections) scaled by A^2 , and the DPS one is the sum of the three terms shown in Fig. 1 which result in the final expression [6]:

$$\sigma_{(AA \rightarrow ab)}^{\text{DPS}} = \left(\frac{m}{2} \right) \frac{\sigma_{(NN \rightarrow a)}^{\text{SPS}} \cdot \sigma_{(NN \rightarrow b)}^{\text{SPS}}}{\sigma_{\text{eff,AA}}}, \text{ with } \sigma_{\text{eff,AA}} = \frac{1}{A^2 \left[\sigma_{\text{eff,pp}}^{-1} + \frac{2}{A} T_{AA}(0) + \frac{1}{2} T_{AA}(0) \right]} \approx 1.5 \, \text{nb}. \quad (3)$$

where $T_{AA}(\mathbf{b})$ is the nuclear overlap function [10] amounting to $T_{AA}(0) = 30.4 \, \text{mb}^{-1}$ for head-on Pb-Pb interactions. The relative contributions of the three terms in the denominator, corresponding to the diagrams of Fig. 1, are approximately 1:4:200. Whereas the single-parton cross sections in Pb-Pb are enhanced by a factor of $A^2 \simeq 4 \cdot 10^4$ compared to that in p-p, the corresponding double-parton cross sections are enhanced by a much higher factor of $\sigma_{\text{eff,pp}}/\sigma_{\text{eff,AA}} \propto A^{3.3}/5 \simeq 9 \cdot 10^6$. Pair-production of pQCD probes issuing from DPS represents thus an important feature of heavy-ion collisions at the LHC and needs to be taken into account in any attempt to fully understand the event-by-event characteristics of any yield suppression and/or enhancement observed in Pb-Pb compared to p-p data.

2. Double parton scatterings in $p\text{-Pb} \rightarrow W^+W^+$ at 8.8 TeV, and in $\text{Pb-Pb} \rightarrow J/\psi J/\psi$ at 5.5 TeV

The production of like-sign WW production –whose cross section has small theoretical uncertainties and a characteristic final-state with same-sign leptons plus (large) missing transverse energy from the undetected neutrinos– has no SPS backgrounds at the same order in α_s , and has been proposed since long as a DPS “smoking gun” in p-p collisions [12]. The DPS signal in p-Pb collisions, $\sigma_{pPb \rightarrow WW}^{\text{DPS}}$, has been computed via Eqs. (2) with NLO single-parton W cross section $\sigma_{pN \rightarrow W}^{\text{SPS}}$ using MCFM 6.2 [13] with CT10 proton [14] and EPS09 nuclear [15] PDF and theoretical scales $\mu = \mu_F = \mu_R = m_W$. Figure 2 (left) shows the total cross sections for all relevant processes in the range of nucleon-nucleon c.m. energies $\sqrt{s_{\text{NN}}} \approx 2\text{--}20$ TeV. At the nominal 8.8 TeV, the same-sign WW DPS cross section is $\sigma_{pPb \rightarrow WW}^{\text{DPS}} \approx 150$ pb (yellow thick curve), i.e. a factor of 1.5 times higher than the SPS background, $\sigma_{pPb \rightarrow WWjj}^{\text{SPS}}$, obtained adding the QCD and electroweak cross sections for the production of W^+W^+ (W^-W^-) plus 2 jets pairs (lowest dashed curve). Accounting for the leptonic decay ratios and applying standard ATLAS/CMS acceptance and reconstruction cuts, one expects about 10 DPS same-sign WW events in 2 pb^{-1} integrated luminosity [5].

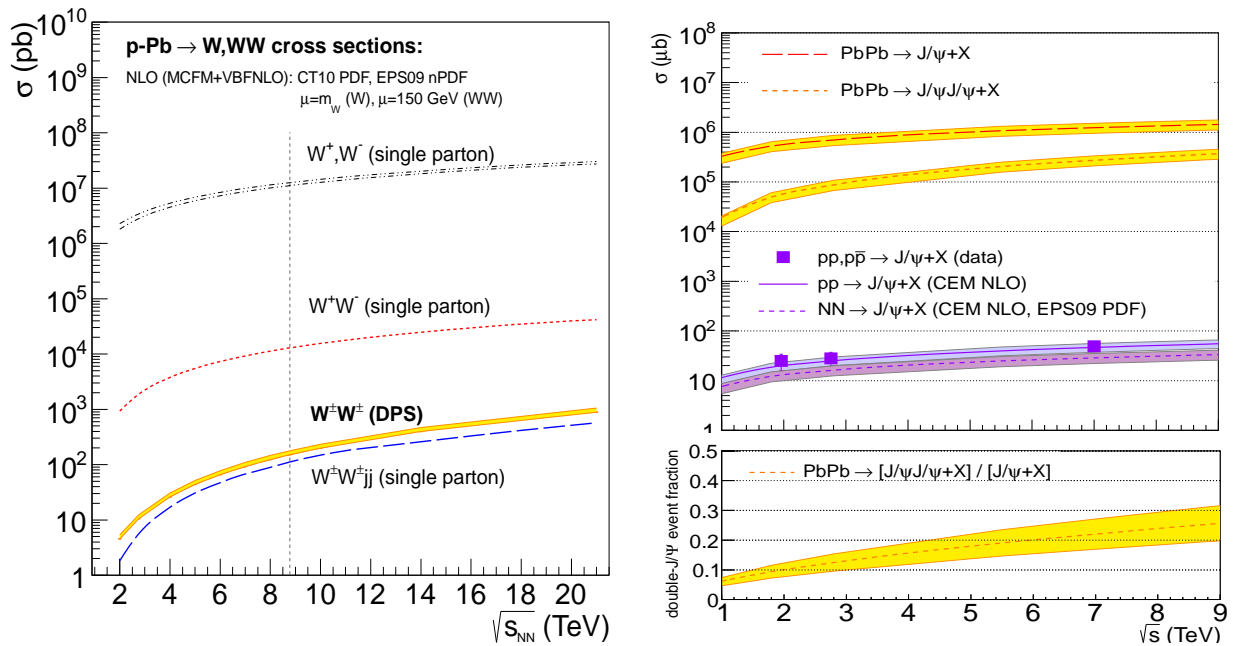


Figure 2. Cross sections as a function of c.m. energy for single-W and W-pair boson(s) in p-Pb for single-parton and double-parton scatterings (left) [5]; and for prompt- J/ψ production in p-p, N-N, and Pb-Pb collisions and for double-parton $J/\psi J/\psi$ in Pb-Pb (right) [6].

The double- J/ψ DPS cross section in Pb-Pb has been computed with Eqs. (3) using the colour evaporation model (CEM) [16], which agrees well with the Tevatron and LHC data (squares in Fig. 2 right), with EPS09 nuclear PDF for the SPS J/ψ cross section, $\sigma_{(NN \rightarrow J/\psi X)}^{\text{SPS}}$. The two top curves in Fig. 2 (right) show the single- J/ψ (dashes) and double- J/ψ (dots) cross sections in Pb-Pb, whereas their ratio is plotted in the bottom panel. At the nominal Pb-Pb energy of 5.5 TeV, single prompt- J/ψ cross sections amount to ~ 1 b, and $\sim 20\%$ of such collisions are accompanied by the production of a second J/ψ from a double parton interaction. The probability of J/ψ - J/ψ DPS production increases rapidly with centrality and at the lowest impact-parameters $\sim 35\%$ of the $\text{Pb-Pb} \rightarrow J/\psi + X$ collisions have a second J/ψ in the final state [6]. Accounting for decays, acceptance and efficiency –which result in a $\sim 3 \cdot 10^{-7}$ reduction factor in the ALICE (forward) and ATLAS/CMS (central) rapidities– the visible cross section is $d\sigma_{J/\psi J/\psi}^{\text{DPS}}/dy|_{y=0.2} \approx 60$ nb per dilepton decay mode, i.e. about 240 double- J/ψ events per unit-rapidity in the four combinations of dielectron and dimuon channels in $\mathcal{L}_{\text{int}} = 1\text{ nb}^{-1}$, assuming no in-medium J/ψ suppression (accounting for it would reduce the yields by a factor of 2). These results show quantitatively that the observation of a J/ψ pair in a given Pb-Pb event should not be (wrongly) interpreted as indicative of J/ψ production via $c\bar{c}$ regeneration in the dense medium created, as DPS are an important component of the total J/ψ yield with or without final-state quark-gluon-plasma effects.

3. Compilation of double-parton scatterings in p-Pb and Pb-Pb

Table 1 collects SPS and DPS cross sections involving J/ψ and electroweak bosons in p-Pb and Pb-Pb collisions at the LHC. The SPS cross sections are computed at NLO (CEM for J/ψ and mCFM for W,Z), and the quoted visible DPS yields (for $\mathcal{L}_{\text{int}} = 1 \text{ pb}^{-1}$ and 1 nb^{-1}) take into account: $\text{BR}(J/\psi, W, Z) = 6\%, 11\%, 3.4\%$ per dilepton decay; and (simplified) acceptance+efficiency losses: $\mathcal{A} \times \mathcal{E}(J/\psi, W, Z) \approx 0.12$ (per unit rapidity), 0.5, 0.5 (full rap.). These estimates indicate that DPS processes leading to double- J/ψ , $J/\psi+W$, $J/\psi+Z$, and same-sign WW, are indeed observable in LHC heavy-ion runs. Other DPS processes like W+Z and Z+Z have lower visible cross sections and are not quoted.

$\sqrt{s_{\text{NN}}}$		$\sigma^{\text{SPS}}(J/\psi)$	$\sigma^{\text{SPS}}(W^+)$	$\sigma^{\text{SPS}}(Z)$		$J/\psi J/\psi$	$J/\psi+W$	$J/\psi+Z$	ss WW	
5.5 TeV	N-N	$25 \mu\text{b}$	30 nb	20 nb	Pb-Pb	σ^{DPS}	200 mb	$500 \mu\text{b}$	$330 \mu\text{b}$	630 nb
						$N^{\text{DPS}}(1 \text{ nb}^{-1})$	~ 240	~ 80	~ 10	~ 20
8.8 TeV	p-N	$45 \mu\text{b}$	60 nb	35 nb	p-Pb	σ^{DPS}	$45 \mu\text{b}$	120 nb	70 nb	140 pb
						$N^{\text{DPS}}(1 \text{ pb}^{-1})$	~ 60	~ 15	~ 2	~ 5

Table 1. Production cross sections of prompt- J/ψ , W and Z bosons in single-parton-scatterings (SPS) in nucleon-nucleon (N-N) and proton-nucleon (p-N) collisions, and of J/ψ - J/ψ , $J/\psi+W$, $J/\psi+Z$, and same-sign WW in double-parton-scatterings (DPS) in Pb-Pb and p-Pb at LHC energies. The corresponding approximate DPS yields (after dilepton decays and acceptance losses) are also given for 1 nb^{-1} and 1 pb^{-1} respectively.

4. Summary

Simple generic expressions to compute the double-parton cross sections in high-energy p-A and A-A collisions have been derived from the corresponding single-parton cross sections. The larger transverse parton density in nuclei results in significantly enhanced cross sections for many DPS processes compared to p-p collisions. Estimates of DPS contributions for (i) same-sign W pair production in p-Pb and (ii) double- J/ψ production in Pb-Pb, have been obtained at LHC energies. The first process can help determine the effective σ_{eff} parameter characterising the transverse parton distribution in the nucleon, and the second one provides interesting insights on the event-by-event dynamics of J/ψ production in Pb-Pb collisions. Many other DPS processes in p-Pb and Pb-Pb (such as $J/\psi+W$, $J/\psi+Z$) have large visible cross sections and are open to study at the LHC.

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